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SAZEL: A COMPUTER PROGRAM TO FIND SUN AZIMUTH AND ELEVATION

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US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
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A computer program, SAZEL, is presented which computes the sun azimuth and elevation angle from an observer's geographic location, local mean time, and calendar date. The method of computing the sun azimuth and elevation angle is discussed in detail and an application of its use is shown.

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FOREWORD

The azimuth and elevation of the sun are routinely determined by a navigator in the air and on the sea to find his vehicle's direction and line of position (LOP). A sun LOP, when used in conjunction with another LOP obtained from other celestial bodies (moon and Venus) or radio navigational aids, enables the navigator to locate his vehicle's position (latitude and longitude).

The method described in this report to find the sun's azimuth and elevation angles is based on a procedure which the author learned during undergraduate Navigator Training at Mather Air Force Base, CA. It is such an easy method that in a minute's time one can obtain the azimuth and elevation angle of the sun by using two tables: The Air Nautical Almanac and the H.O. 249 Sight Reduction Table.

Rather than manually extracting data from the tables, the necessary celestial mechanics and solar motion data have been programmed into a computer program, SAZEL. One need only know the time of day, position, and date to obtain positional data for the sun.

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INTRODUCTION

To obtain data on rotational motions of projectiles in free flight, a device called a "yaw sonde" is used. The working details of the yaw sonde are described in references 1 through 4. Attitude data are obtained during the flight of a missile by making repeated measurements of the angle between the longitudinal axis of the missile and the sun. Any change in this angle can be approximated by a change in attitude of the missile, since the sun moves infinitesimally during a projectile's flight time.

In order for the yaw sonde to obtain measurements, it is necessary that the sun be within the field of view scanned by the yaw sonde during the flight of the missile. The interval between the first and last times the sun appears in the field of view for the interesting parts of the trajectory on a given day and at a given location is the "window". To determine the window, the sun position (consisting of azimuth and elevation) must be known or computed from other sun data. References 5 through 7 present various computer methods of determining the window. Common to every method, however, is a requirement for selected input data relative to the sun, which is obtained from references 8 and 9.

This report describes various methods of determining the sun's azimuth and elevation (for any year from 1965 through 2000) and, by the use of the computer program SAZEL, eliminates the requirement for input data obtained from references 8 and 9.

DISCUSSION

Sun Features

The sun exhibits certain features that contribute to its use in the yaw sonde method of measuring missile attitude:

1. Its position can be determined accurately at any instant in time.

2. A change in its position, in relation to the earth, is of so short a duration as to be negligible during the flight of most missiles.

3. It provides ample energy for the functioning of the yaw sonde.

Sun Acquisition by a Yaw Sonde

The signals produced by the yaw sonde can be reduced to the spin rate of the projectile and the angle, γ, between the sun vector and the longitudinal axis of the projectile; or the angle, σ, between the sun vector and a normal-to-the projectile axis (fig 2). The convention adopted here is that σ is positive if the sun is toward the nose of the projectile and

$$\sigma = 90^\circ - \gamma \tag{1}$$

The ARRADCOM yaw sonde is capable of accepting values of γ from 30° to 145°; then σ may vary from -55° to +60°.

Data reduction of signals for a typical 155 mm M549 projectile in free flight, using a yaw sonde, are then plotted against the time required to study the dynamic behavior throughout its trajectory. Figures 4 and 5 show, respectively, the spin (PHI DOT) and the angular motion (Sigma N) vs time (ref 10).

Time Computation

The Greenwich Mean Time (GMT) of a firing is found by noting the Local Mean Time (LMT) at the instant of firing and converting as follows:

$$\text{GMT} = \text{LMT} + \text{IZREF (West Longitude)} \tag{2a}$$

$$\text{GMT} = \text{LMT} - \text{IZREF (East Longitude)} \tag{2b}$$

Values of IZREF for each state in the U.S. are given in table 1. For locations outside the U.S., the value of IZREF can be found in reference 8. As an example, the GMT at Yuma Proving Ground, Arizona, for LMT equals 0830 is found to be 1530 since IZREF equals 0700 according to table 1.

Celestial Angle Relations

Figure 1 shows the angular position of the sun and the observer with reference to the earth, along with the symbols and sign conventions. The positional system employed here (ref 12) is one which easily defines the position of an observer on the earth by latitude and longitude. A point on the earth directly beneath the sun, its subpoint (SS, fig 1), could just as easily be defined by its latitude and longitude. The usual point of reference for longitude (fig 1) is the Greenwich Meridian (GM) 0° longitude. The longitude component of the position of the sun's subpoint, SS, is usually expressed as a hour angle either from the Greenwich Meridian (the Greenwich Hour Angle, GHA) or from the observer's

meridan (the Local Hour Angle, LHA). Longitude is measured east or west from 0° through 180°, but hour angles are always measured westward, either from GM or the observer's meridian from 0° through 360°. The Local Hour Angle is computed as follows:

$$LHA = GHA - \text{West Longitude} \tag{3a}$$

$$LHA = GHA + \text{East Longitude} \tag{3b}$$

Many angular measurements, such as those shown in figure 1, are referenced to the equator (e.g., the latitude of the observer and the declination (Dec) of the sun) or to the celestial horizon for the elevation of the sun. The declination of the sun is also the latitude of its subpoint. Latitude is measured north or south of the equator, 0° through 90° at the poles. Declination is limited to approximately 23½° travel north or south of the equator (due to the orbit of the earth about the sun and the tilt of the earth's north-south axis).

Finally, we need to define the angular direction in which to look for the sun. Figure 3 shows that the azimuth of the sun, ZN, from an observer's position, is measured clockwise from north to a line joining the observer's position and the subpoint of the sun.

Determination of GHA and Declination of the Sun

Two methods of finding the GHA and Dec of the sun are presented. The first method requires a simple reference to the Air Nautical Almanac for a specific date and GMT. [Table 2 is extracted from the almanac (ref 8).] As an example, for 28 Oct 1978 at 1530 GMT, the almanac states that the GHA equals 56° 32.5' (56.542°) and the Dec = S 13° 08.4' (-13.14°). The second method (ref 11) employs the use of table 3 and is explained in the table. It is an emergency method of computing the sun's GHA and Dec if the almanac is not available. At first glance, it seems cumbersome; but, with practice, the computation is accomplished in a minute's time. Using the same example as above and following the explanation in table 3, we would compute GHA equals 56° 33' (56.55°) and Dec equals S 13° 09' (-13.15°). This method has been programmed into the computer program, SAZEL. User input to the program is explained in appendix A and a listing of SAZEL is provided in appendix B.

Determination of the Sun's LHA, Elevation, and Azimuth

Once the GHA and Dec of the sun have been found, based on the date and GMT, the azimuth (ZN) and elevation (HC) of the sun can be found if we know the latitude and longitude of the observer. Through the use of the Sight Reduction Tables for Air Navigation (ref 11),

we can find the azimuth and elevation of the sun. (Table 4 is an extract from reference 11 to use as an example.) Using the GHA and Dec found earlier, and placing the observer at Yuma Proving Ground, latitude equals 32.8811° and longitude equals 114.3028°, we proceed to find the LHA using equation 3a, thus

$$LHA = 56.5500^\circ - 114.3028^\circ$$

$$LHA = 302.2472^\circ \text{ (360° has been added to make LHA positive)}$$

Entering table 4 with the LHA, Dec, and latitude, we find the azimuth and elevation of the sun by interpolation; thus, HO = 18° 11' and Z = ZN = 120°. The computer program, SAZEL, computes HC and ZN using rudimentary principles of trigonometry.

Six Degrees-of-Freedom Simulation of Free Flight Missile Using SAZEL

For a simulated trajectory of a free flight missile, using a modified six degrees-of-freedom (6-DOF) trajectory program (ref 13) and SAZEL, the angular motion, σ, can be plotted against time as shown in figure 6. Figure 6 represents a simulation of the 155 mm M549 projectile which was fired at Yuma Proving Ground (ref 10) compared to the actual recorded angular motion shown in figure 4. The azimuth and elevation of the sun can be represented by a vector S, as shown in figure 3. The vector S can further be represented by unit vector components S1, S2, and S3. The attitude of the missile, as contained in reference 13, is represented by the vector P. Vector P is also represented by its unit vector components P1, P2, and P3. The dot product of these unit vectors enables us to find γ and finally, σ, which we are ultimately interested in plotting against time. S1, S2, and S3 in the earth frame are as follows:

$$S1 = \cos HC \cos ZN \tag{4a}$$

$$S2 = \sin HC \tag{4b}$$

$$S3 = \cos HC \sin ZN \tag{4c}$$

The angle γ is then computed as follows:

$$\gamma = \arccos (S1P1 + S2P2 + S3P3)$$

and ultimately we find σ from equation 1.

Accuracy

The calibration of the yaw sonde is such that system acquisition has been reported to be ± ¼°. The method of computation using SAZEL is reported in the Air Nautical Almanac to be ± 1' (0.017°) for GHA and ± 2' (0.033°) for Dec of the sun. Small errors in the computation of azimuth and elevation would be inherent due to GHA and Dec from the above computation and changing missile position. The effect of changing latitude and longitude after launch on the computation of GHA, LHA, HC, and ZN, can be minimized by using the latitude and longitude at the midpoint of a trajectory. Another error is introduced through the necessary assumption of unchanging altitude from ground level. Finally, an error which affects both computation of sun elevation and data acquisition is atmospheric refraction. Refraction is a complicated function of height above the earth and apparent elevation of the sun. The refraction is further dependent on the temperature of the atmosphere at the height of observation. At any given apparent sun elevation, the refraction decreases with increasing altitude. Refraction is further decreased if the atmosphere is warmer than normal at the height of observation. For the flight of most missiles, the refraction encountered should be no greater than -20' (0.333°) under the worst conditions--sea level, colder than normal atmosphere, and sun on the horizon.

The overall error for ranges under 30km and altitudes from ground level to 30 km, using the midpoint trajectory latitude and longitude, is estimated to be ± ½° for any simulation.

RESULTS

The reader can compare the manual method of computation for LHA, GHA, AZ and HC to that derived from SAZEL. Very close agreement is shown between the results obtained from the SAZEL program (app A) and those extracted from the Air Almanac and Sightreading Tables, as follows:

Source	LHA (computed)	GHA	DEC	AZ	HC
Air Almanac		56.5417°	-13,1400°		
Sightreading Tables	302.2472°	56.5500°	-13.1500°		
Sight Reduction Method	302.2472°			120.0000°	18.1833°
SAZEL		56.5333°	-13.1392°	119.8569°	18.2251°

Comparing the actual angular motion in figure 4 to the simulated angular motion in figure 6, close agreement is obvious. Note that the actual flight would result in Sigma N from the apparent sun due to refraction. A suitable aerodynamic coefficient package and the test data (record of firing data for the actual flight) are necessary to obtain accurate results.

CONCLUSIONS

SAZEL, a computer program, has been developed which determines the azimuth and elevation angles of the sun quickly and accurately, without using tabulated sun data available in the published literature. In comparison with the yaw-sonde method (which does rely on previously published data), SAZEL has been demonstrated to be a viable tool in simulating the angular motion of missiles during free flight.

RECOMMENDATIONS

1. Update, with SAZEL, the ARRADCOM computer program for determining appropriate times (windows) for firing projectiles equipped with yaw sondes. (The trial version is now working.)

2. Complete the 6-DOF trajectory program using SAZEL which allows computation of projectile angular motion motion (yaw sonde sun angle, Sigma N) vs time for plotting on the ARRADCOM graphics terminal. (The trial version is now working.)

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Table 1. IZREF conversion from local time to Greenwich time

STATE	IZREF
Alabama[1]	0600
Alaska[1], east of long. W. 137°	0800
long. W. 137° to W. 141°	0900
long. W. 141° to W. 161°	1000
long. W. 161° to W. 172°	1100
Aleutian Islands	1100
Arizona	0700
Arkansas[1]	0600
California[1]	0800
Colorado[1]	0700
Connecticut[1]	0500
Delaware[1]	0500
District of Columbia[1]	0500
Florida[1,2]	0500
Georgia[1]	0500
Hawaii	1000
Idaho[1,2]	0700
Illinois[1]	0600
Indiana[2]	0500
Iowa[1]	0600
Kansas[1,2]	0600
Kentucky[1,2]	0500
Louisiana[1]	0600
Maine[1]	0500
Maryland[1]	0500
Massachusetts[1]	0500
Michigan	0500
Minnesota[1]	0600
Mississippi[1]	0600
Missouri[1]	0600
Montana[1]	0700
Nebraska[1,2]	0600
Nevada[1]	0800
New Hampshire[1]	0500
New Jersey[1]	0500
New Mexico[1]	0700
New York[1]	0500
North Carolina[1]	0500
North Dakota[1,2]	0600
Ohio[1]	0500
Oklahoma[1]	0600
Oregon[1,2]	0800
Pennsylvania[1]	0500
Rhode Island[1]	0500
South Carolina[1]	0500
South Dakota[1], eastern part	0600
western part	0700
Tennessee[1,2]	0600
Texas[1]	0600
Utah[1,2]	0700
Vermont[1]	0500
Virginia[1]	0500
Washington, D.C.[1]	0500
Washington[1]	0800
West Virginia[1]	0500
Wisconsin[1]	0600
Wyoming[1]	0700

[1]Summer (daylight-saving) time, one hour fast on the time given (-100) is kept in these states from the last Sunday in April to the last Sunday in October, changing at $02^h\ 00^m$ local clock time.

[2]This applies to the greater portion of the state.

Table 2. Extract from Air Nautical Almanac

602 (DAY 301) GREENWICH P. M. 1978 OCTOBER 28 (SATURDAY)

GMT	☉ SUN GHA	SUN Dec.	ARIES GHA	VENUS −4.0 GHA	VENUS Dec.	JUPITER −1.7 GHA	JUPITER Dec.	SATURN 1.1 GHA	SATURN Dec.	◐ MOON GHA	MOON Dec.
h m	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′
12 00	4 02.3	S13 05.5	216 28.6	350 05	S24 04	86 11	N18 41	53 18	N 8 52	41 48	N 2 05
10	6 32.3	05.7	218 59.0	352 35		88 41		55 48		44 13	03
20	9 02.3	05.8	221 29.5	355 06		91 12		58 19		46 38	02
30	11 32.3	· 05.9	223 59.9	357 36	· ·	93 42	· ·	60 49	· ·	49 04	2 00
40	14 02.4	06.1	226 30.3	0 07		96 12		63 19		51 29	1 59
50	16 32.4	06.2	229 00.7	2 37		98 43		65 50		53 55	57
13 00	19 02.4	S13 06.4	231 31.1	5 08	S24 04	101 13	N18 41	68 20	N 8 52	56 20	N 1 55
10	21 32.4	06.5	234 01.5	7 38		103 43		70 51		58 45	54
20	24 02.4	06.6	236 31.9	10 09		106 14		73 21		61 11	52
30	26 32.4	· 06.8	239 02.3	12 40	· ·	108 44	· ·	75 51	· ·	63 36	· 50
40	29 02.4	06.9	241 32.7	15 10		111 15		78 22		66 02	49
50	31 32.4	07.1	244 03.2	17 41		113 45		80 52		68 27	47
14 00	34 02.4	S13 07.2	246 33.6	20 11	S24 03	116 15	N18 41	83 23	N 8 52	70 52	N 1 45
10	36 32.4	07.3	249 04.0	22 42		118 46		85 53		73 18	44
20	39 02.4	07.5	251 34.4	25 12		121 16		88 23		75 43	42
30	41 32.4	· 07.6	254 04.8	27 43	· ·	123 46	· ·	90 54	· ·	78 09	· 40
40	44 02.5	07.7	256 35.2	30 14		126 17		93 24		80 34	39
50	46 32.5	07.9	259 05.6	32 44		128 47		95 54		83 00	37
15 00	49 02.5	S13 08.0	261 36.0	35 15	S24 03	131 18	N18 41	98 25	N 8 52	85 25	N 1 36
10	51 32.5	08.2	264 06.4	37 45		133 48		100 55		87 50	34
20	54 02.5	08.3	266 36.8	40 16		136 18		103 25		90 16	32
⇒ 30	56 32.5	· 08.4	269 07.3	42 47	· ·	138 49	· ·	105 56	· ·	92 41	· 31
40	59 02.5	08.6	271 37.7	45 17		141 19		108 26		95 07	29
50	61 32.5	08.7	274 08.1	47 48		143 49		110 57		97 32	27
16 00	64 02.5	S13 08.9	276 38.5	50 18	S24 02	146 20	N18 41	113 27	N 8 52	99 57	N 1 26
10	66 32.5	09.0	279 08.9	52 49		148 50		115 57		102 23	24
20	69 02.5	09.1	281 39.3	55 19		151 21		118 28		104 48	22
30	71 32.5	· 09.3	284 09.7	57 50	· ·	153 51	· ·	120 58	· ·	107 14	· 21
40	74 02.6	09.4	286 40.1	60 21		156 21		123 28		109 39	19
50	76 32.6	09.6	289 10.5	62 51		158 52		125 59		112 04	17
17 00	79 02.6	S13 09.7	291 41.0	65 22	S24 02	161 22	N18 41	128 29	N 8 52	114 30	N 1 16
10	81 32.6	09.8	294 11.4	67 52		163 52		131 00		116 55	14
20	84 02.6	10.0	296 41.8	70 23		166 23		133 30		119 20	12
30	86 32.6	· 10.1	299 12.2	72 53	· ·	168 53	· ·	136 00	· ·	121 46	· 11
40	89 02.6	10.3	301 42.6	75 24		171 24		138 31		124 11	09
50	91 32.6	10.4	304 13.0	77 55		173 54		141 01		126 37	08
18 00	94 02.6	S13 10.5	306 43.4	80 25	S24 01	176 24	N18 41	143 32	N 8 52	129 02	N 1 06
10	96 32.6	10.7	309 13.8	82 56		178 55		146 02		131 27	04
20	99 02.6	10.8	311 44.2	85 26		181 25		148 32		133 53	03
30	101 32.6	· 11.0	314 14.7	87 57	· ·	183 55	· ·	151 03	· ·	136 18	1 01
40	104 02.6	11.1	316 45.1	90 27		186 26		153 33		138 44	0 59
50	106 32.7	11.2	319 15.5	92 58		188 56		156 03		141 09	58
19 00	109 02.7	S13 11.4	321 45.9	95 29	S24 00	191 27	N18 41	158 34	N 8 52	143 34	N 0 56
10	111 32.7	11.5	324 16.3	97 59		193 57		161 04		146 00	54
20	114 02.7	11.7	326 46.7	100 30		196 27		163 34		148 25	53
30	116 32.7	· 11.8	329 17.1	103 00	· ·	198 58	· ·	166 05	· ·	150 51	· 51
40	119 02.7	11.9	331 47.5	105 31		201 28		168 35		153 16	49
50	121 32.7	12.1	334 17.9	108 02		203 58		171 06		155 41	48
20 00	124 02.7	S13 12.2	336 48.3	110 32	S24 00	206 29	N18 41	173 36	N 8 52	158 07	N 0 46
10	126 32.7	12.3	339 18.8	113 03		208 59		176 06		160 32	44
20	129 02.7	12.5	341 49.2	115 33		211 30		178 37		162 57	43
30	131 32.7	· 12.6	344 19.6	118 04	· ·	214 00	· ·	181 07	· ·	165 23	· 41
40	134 02.7	12.8	346 50.0	120 34		216 30		183 37		167 48	39
50	136 32.7	12.9	349 20.4	123 05		219 01		186 08		170 14	38
21 00	139 02.8	S13 13.0	351 50.8	125 36	S23 59	221 31	N18 41	188 38	N 8 52	172 39	N 0 36
10	141 32.8	13.2	354 21.2	128 06		224 01		191 09		175 04	34
20	144 02.8	13.3	356 51.6	130 37		226 32		193 39		177 30	33
30	146 32.8	· 13.5	359 22.0	133 07	· ·	229 02	· ·	196 09	· ·	179 55	· 31
40	149 02.8	13.6	1 52.5	135 38		231 33		198 40		182 20	29
50	151 32.8	13.7	4 22.9	138 09		234 03		201 10		184 46	28
22 00	154 02.8	S13 13.9	6 53.3	140 39	S23 59	236 33	N18 41	203 41	N 8 52	187 11	N 0 26
10	156 32.8	14.0	9 23.7	143 10		239 04		206 11		189 37	24
20	159 02.8	14.2	11 54.1	145 40		241 34		208 41		192 02	23
30	161 32.8	· 14.3	14 24.5	148 11	· ·	244 04	· ·	211 12	· ·	194 27	· 21
40	164 02.8	14.4	16 54.9	150 41		246 35		213 42		196 53	19
50	166 32.8	14.6	19 25.3	153 12		249 05		216 12		199 18	18
23 00	169 02.8	S13 14.7	21 55.7	155 43	S23 58	251 36	N18 41	218 43	N 8 51	201 43	N 0 16
10	171 32.9	14.9	24 26.1	158 13		254 06		221 13		204 09	14
20	174 02.9	15.0	26 56.6	160 44		256 36		223 43		206 34	13
30	176 32.9	· 15.1	29 27.0	163 14	· ·	259 07	· ·	226 14	· ·	208 59	· 11
40	179 02.9	15.3	31 57.4	165 45		261 37		228 44		211 25	09
50	181 32.9	15.4	34 27.8	168 15		264 07		231 15		213 50	08
Rate	15 00.0	S0 00.8		15 03.5	N0 00.5	15 02.2	S0 00.1	15 02.3	S0 00.1	14 32.3	S0 09.9

Lat.	Moon-set	Diff.
N		
°	h m	m
72	15 37	−02
70	15 35	00
68	15 33	+03
66	15 32	05
64	15 31	06
62	15 30	07
60	15 29	09
58	15 28	10
56	15 27	11
54	15 27	12
52	15 26	12
50	15 26	13
45	15 25	15
40	15 24	16
35	15 23	17
30	15 22	18
20	15 21	20
10	15 20	22
0	15 18	23
10	15 17	25
20	15 16	26
30	15 15	28
35	15 14	29
40	15 13	30
45	15 12	31
50	15 10	33
52	15 10	34
54	15 09	35
56	15 08	35
58	15 08	37
60	15 07	38
S		

Moon's P. in A.

Alt.	Corr.	Alt.	Corr.
°	+ ′	°	+ ′
0		55	
	56		31
7		56	
	55		30
13		58	
	54		29
16		59	
	53		28
20		60	
	52		27
22		61	
	51		26
25		62	
	50		25
27		64	
	49		24
29		65	
	48		23
31		66	
	47		22
33		67	
	46		21
35		68	
	45		20
37		69	
	44		19
38		70	
	43		18
40		71	
	42		17
42		72	
	41		16
43		73	
	40		15
45		74	
	39		14
46		76	
	38		13
47		77	
	37		12
49		78	
	36		11
50		79	
	35		10
51		80	
	34		
53			
	33		
54			
	32		
55			
	31		
56			

Sun SD 16′.1
Moon SD 15′
Age 26d

Table 3. GHA and declination of the sun for the years 1965-2000

(a) Interpolation for E and Dec

CT 00h	JAN E	JAN Dec.	d	FEB E	FEB Dec.	d	MAR E	MAR Dec.	d	APR E	APR Dec.	d	MAY E	MAY Dec.	d	JUN E	JUN Dec.	d
d	° ′	° ′		° ′	° ′		° ′	° ′		° ′	° ′		° ′	° ′		° ′	° ′	
1	4 11	S 23 03	5	1 37	S 17 16	17	1 52	S 7 49	23	3 58	N 4 18	24	5 42	N 14 54	18	5 36	N 21 58	8
2	4 04	22 58	5	1 35	16 59	17	1 55	7 26	23	4 02	4 42	23	5 44	15 12	18	5 33	22 06	8
3	3 57	22 53	6	1 33	16 42	18	1 58	7 03	23	4 07	5 05	23	5 46	15 30	17	5 31	22 14	8
4	3 50	22 47	6	1 31	16 24	18	2 01	6 40	23	4 11	5 28	23	5 48	15 47	18	5 28	22 22	7
5	3 43	22 41	7	1 30	16 06	18	2 04	6 17	23	4 16	5 51	22	5 49	16 05	17	5 26	22 29	6
6	3 36	S 22 34	7	1 29	S 15 48	18	2 07	S 5 54	23	4 20	N 6 13	23	5 50	N 16 22	17	5 23	N 22 35	7
7	3 30	22 27	8	1 28	15 30	19	2 11	5 31	24	4 24	6 36	23	5 51	16 39	16	5 21	22 42	5
6	3 23	22 19	8	1 27	15 11	19	2 14	5 07	23	4 28	6 59	22	5 52	16 55	17	5 18	22 47	6
9	3 17	22 11	8	1 26	14 52	19	2 18	4 44	24	4 33	7 21	22	5 53	17 12	16	5 15	22 53	5
10	3 11	22 03	9	1 26	14 33	20	2 22	4 20	23	4 37	7 43	23	5 54	17 28	15	5 12	22 58	5
11	3 05	S 21 54	10	1 26	S 14 13	20	2 26	S 3 57	24	4 41	N 8 06	22	5 55	N 17 43	16	5 09	N 23 03	4
12	2 59	21 44	9	1 26	13 53	20	2 30	3 33	23	4 45	8 28	22	5 55	17 59	15	5 06	23 07	4
13	2 53	21 35	10	1 26	13 33	20	2 34	3 10	24	4 49	8 50	21	5 56	18 14	15	5 03	23 11	3
14	2 47	21 25	11	1 26	13 13	20	2 38	2 46	24	4 53	9 11	22	5 56	18 29	14	5 00	23 14	3
15	2 42	21 14	11	1 27	12 53	21	2 42	2 22	23	4 56	9 33	21	5 56	18 43	15	4 57	23 17	3
16	2 37	S 21 03	11	1 27	S 12 32	20	2 46	S 1 59	24	5 00	N 9 54	22	5 56	N 18 58	13	4 54	N 23 20	2
17	2 31	20 52	12	1 28	12 12	21	2 50	1 35	24	5 04	10 16	21	5 55	19 11	14	4 50	23 22	2
16	2 26	20 40	12	1 29	11 51	22	2 55	1 11	23	5 07	10 37	21	5 55	19 25	13	4 47	23 24	1
19	2 22	20 28	13	1 30	11 29	21	2 59	0 48	24	5 10	10 58	21	5 54	19 38	13	4 44	23 25	1
20	2 17	20 15	13	1 32	11 08	22	3 04	S 0 24	24	5 14	11 19	20	5 54	19 51	13	4 41	23 26	0
21	2 13	S 20 02	13	1 33	S 10 46	21	3 08	0 00	24	5 17	N 11 39	21	5 53	N 20 04	12	4 37	N 23 26	1
22	2 08	19 49	14	1 35	10 25	22	3 12	N 0 24	23	5 20	12 00	20	5 52	20 16	12	4 34	23 27	1
23	2 04	19 35	14	1 37	10 03	22	3 17	0 47	24	5 23	12 20	20	5 51	20 28	11	4 31	23 26	1
24	2 00	19 21	14	1 39	9 41	22	3 22	1 11	24	5 26	12 40	20	5 50	20 39	11	4 28	23 25	1
25	1 57	19 07	15	1 41	9 19	23	3 26	1 35	23	5 29	13 00	19	5 48	20 50	11	4 24	23 24	1
26	1 53	S 18 52	15	1 44	S 8 56	22	3 31	N 1 58	24	5 31	N 13 19	19	5 47	N 21 01	11	4 21	N 23 23	2
27	1 50	18 37	16	1 46	8 34	23	3 35	2 22	23	5 34	13 38	20	5 45	21 12	10	4 18	23 21	2
26	1 47	18 21	16	1 49	8 11	22	3 40	2 45	24	5 36	13 58	19	5 44	21 22	9	4 15	23 19	3
29	1 44	18 05	16	1 52	7 49	23	3 44	3 09	23	5 38	14 17	18	5 42	21 31	10	4 12	23 16	3
30	1 41	17 49	16				3 49	3 32	23	5 40	14 35	19	5 40	21 41	9	4 09	23 13	4
31	1 39	S 17 33	17				3 53	N 3 55	23				5 38	N 21 50	8			

DT 00h	JUL E	JUL Dec.	d	AUG E	AUG Dec.	d	SEP E	SEP Dec.	d	OCT E	OCT Dec.	d	NOV E	NOV Dec.	d	DEC E	DEC Dec.	d
d	° ′	° ′		° ′	° ′		° ′	° ′		° ′	° ′		° ′	° ′		° ′	° ′	
1	4 06	N 23 09	4	3 25	N 18 10	15	4 57	N 8 30	22	7 31	S 2 57	23	9 05	S 14 14	19	7 48	S 21 42	10
2	4 03	23 05	4	3 26	17 55	15	5 01	8 08	21	7 36	3 20	24	9 06	14 33	19	7 43	21 52	9
3	4 00	23 01	5	3 27	17 40	16	5 06	7 47	22	7 41	3 44	23	9 06	14 52	19	7 37	22 01	8
4	3 57	22 56	5	3 28	17 24	16	5 11	7 25	23	7 45	4 07	23	9 06	15 11	19	7 31	22 09	8
5	3 55	22 51	6	3 30	17 08	16	5 16	7 02	22	7 50	4 30	23	9 06	15 30	18	7 25	22 17	8
6	3 52	N 22 45	6	3 31	N 16 52	16	5 21	N 6 40	22	7 55	S 4 53	23	9 05	S 15 48	18	7 19	S 22 25	7
7	3 49	22 39	6	3 33	16 36	17	5 26	6 18	23	7 59	5 16	23	9 05	16 06	18	7 12	22 32	7
8	3 47	22 33	7	3 35	16 19	17	5 31	5 55	22	8 03	5 39	23	9 04	16 24	17	7 06	22 39	7
9	3 45	22 26	7	3 37	16 02	17	5 36	5 33	23	8 07	6 02	23	9 03	16 41	17	7 00	22 46	5
10	3 42	22 19	8	3 39	15 45	18	5 41	5 10	23	8 12	6 25	22	9 02	16 58	17	6 53	22 51	6
11	3 40	N 22 11	8	3 41	N 15 27	18	5 47	N 4 47	22	8 16	S 6 47	23	9 00	S 17 15	17	6 46	S 22 57	5
12	3 38	22 03	8	3 43	15 09	18	5 52	4 25	23	8 19	7 10	23	8 59	17 32	16	6 39	23 02	4
13	3 36	21 55	9	3 46	14 51	18	5 57	4 02	23	8 23	7 33	22	8 57	17 48	16	6 32	23 06	5
14	3 35	21 46	9	3 48	14 33	18	6 02	3 39	23	8 27	7 55	22	8 55	18 04	16	6 25	23 11	3
15	3 33	21 37	9	3 51	14 15	19	6 08	3 16	23	8 30	8 17	23	8 52	18 20	15	6 18	23 14	3
16	3 31	N 21 26	10	3 54	N 13 56	19	6 13	N 2 53	23	8 34	S 8 40	22	8 50	S 18 35	15	6 11	S 23 17	3
17	3 30	21 18	10	3 57	13 37	19	6 18	2 30	24	8 37	9 02	22	8 47	18 50	15	6 03	23 20	2
18	3 29	21 08	10	4 00	13 18	19	6 24	2 06	23	8 40	9 24	22	8 44	19 05	14	5 56	23 22	2
19	3 28	20 58	11	4 04	12 59	20	6 29	1 43	23	8 43	9 46	21	8 41	19 19	14	5 49	23 24	1
20	3 27	20 47	11	4 07	12 39	20	6 34	1 20	23	8 46	10 07	22	8 38	19 33	14	5 41	23 25	1
21	3 26	N 20 36	12	4 11	N 12 19	20	6 40	N 0 57	24	8 48	S 10 29	21	8 34	S 19 47	13	5 34	S 23 26	1
22	3 25	20 24	12	4 14	11 59	20	6 45	0 33	23	8 51	10 50	21	8 30	20 00	13	5 26	23 27	1
23	3 24	20 12	12	4 18	11 39	20	6 50	N 0 10	23	8 53	11 11	22	8 26	20 13	13	5 19	23 26	0
24	3 24	20 00	13	4 22	11 19	21	6 56	S 0 13	24	8 55	11 33	20	8 22	20 26	12	5 11	23 26	1
25	3 24	19 47	13	4 26	10 58	20	7 01	0 37	23	8 57	11 53	21	8 18	20 38	11	5 04	23 25	2
26	3 23	N 19 34	13	4 30	N 10 38	21	7 08	S 1 00	24	8 59	S 12 14	21	8 14	S 20 49	12	4 57	S 23 23	2
27	3 23	19 21	13	4 34	10 17	21	7 11	1 24	23	9 00	12 35	20	8 09	21 01	11	4 49	23 21	2
28	3 23	19 08	14	4 38	9 56	21	7 16	1 47	23	9 02	12 55	20	8 04	21 12	11	4 42	23 19	3
29	3 24	18 54	14	4 43	9 35	22	7 21	2 10	24	9 03	13 15	20	7 59	21 23	10	4 34	23 16	4
30	3 24	18 40	15	4 47	9 13	21	7 26	2 34	23	9 04	13 35	20	7 54	21 33	9	4 27	23 12	4
31	3 25	N 18 25	15	4 52	N 8 52	22				9 05	S 13 55	19				4 20	S 23 08	4

(b) Corr. to GMT

Year	Corr.	Year	Corr.	Year	Corr.
	h		h		h
1965	+ 4	1977	+ 7	1989	+ 9
1966	− 1	1978	+ 1	1990	+ 3
1967	− 7	1979	− 5	1991	− 3
1968	−13	1980	−11	1992	− 9
"	+11*	"	+13*	"	+15*
1969	+ 5	1981	+ 7	1993	+10
1970	− 1	1982	+ 1	1994	+ 4
1971	− 7	1983	− 4	1995	− 2
1972	−12	1984	−10	1996	− 8
"	+12*	"	+14*	"	+16*
1973	+ 6	1985	+ 8	1997	+10
1974	0	1986	+ 2	1998	+ 4
1975	− 6	1987	− 4	1999	− 1
1976	−12	1988	− 9	2000	− 7
"	+12*	"	+15*	"	+17*

* After Feb. 29

(c) Interpolation for Hours of O.T.

Diff.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
h	′	′	′	′	′	′	′	′	′	′	′	′	′	′	′	′	′	′	′	′	′	′	′	′
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1
2	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2
3	0	0	0	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	3	3	3	3	3
4	0	0	1	1	1	1	1	1	2	2	2	2	2	2	3	3	3	3	3	3	4	4	4	4
5	0	0	1	1	1	1	1	2	2	2	2	3	3	3	3	3	4	4	4	4	4	5	5	5
6	0	1	1	1	1	2	2	2	2	3	3	3	3	4	4	4	4	5	5	5	5	6	6	6
7	0	1	1	1	1	2	2	2	3	3	3	4	4	4	4	5	5	5	6	6	6	6	7	7
8	0	1	1	1	2	2	2	3	3	3	4	4	4	5	5	5	6	6	6	7	7	7	8	8
9	0	1	1	2	2	2	3	3	3	4	4	5	5	5	6	6	6	7	7	8	8	8	9	9
10	0	1	1	2	2	3	3	3	4	4	5	5	5	6	8	7	7	8	8	8	9	9	10	10
11	0	1	1	2	2	3	3	4	4	5	5	6	6	6	7	7	8	8	9	9	10	10	11	11
12	1	1	2	2	3	3	4	4	5	5	6	6	7	7	8	8	9	9	10	10	11	11	12	12
13	1	1	2	2	3	3	4	4	5	5	6	7	7	8	8	9	9	10	10	11	11	12	12	13
14	1	1	2	2	3	4	4	5	5	6	6	7	8	8	9	9	10	11	11	12	12	13	13	14
15	1	1	2	3	3	4	4	5	6	6	7	8	8	9	9	10	11	11	12	13	13	14	14	15
16	1	1	2	3	3	4	5	5	6	7	7	8	9	9	10	11	11	12	13	13	14	15	15	16
17	1	1	2	3	4	4	5	6	6	7	8	9	9	10	11	11	12	13	13	14	15	16	16	17
18	1	2	2	3	4	5	5	6	7	8	8	9	10	11	11	12	13	14	14	15	16	17	17	18
19	1	2	2	3	4	5	6	6	7	8	9	10	10	11	12	13	13	14	15	16	17	17	18	19
20	1	2	3	3	4	5	6	7	8	8	9	10	11	12	13	13	14	15	16	17	18	18	19	20
21	1	2	3	4	4	5	6	7	8	9	10	11	11	12	13	14	15	16	17	18	18	19	20	21
22	1	2	3	4	5	6	6	7	8	9	10	11	12	13	14	15	16	17	17	18	19	20	21	22
23	1	2	3	4	5	6	7	8	9	10	11	12	12	13	14	15	16	17	18	19	20	21	22	23

Table 3. (Cont'd)

(d) Hours and Tens of Minutes of GMT

h	00m ° ′	10m ° ′	20m ° ′	30m ° ′	40m ° ′	50m ° ′
00	175 00	177 30	180 00	182 30	185 00	187 30
01	190 00	192 30	195 00	197 30	200 00	202 30
02	205 00	207 30	210 00	212 30	215 00	217 30
03	220 00	222 30	225 00	227 30	230 00	232 30
04	235 00	237 30	240 00	242 30	245 00	247 30
05	250 00	252 30	255 00	257 30	260 00	262 30
06	265 00	267 30	270 00	272 30	275 00	277 30
07	280 00	282 30	285 00	287 30	290 00	292 30
08	295 00	297 30	300 00	302 30	305 00	307 30
09	310 00	312 30	315 00	317 30	320 00	322 30
10	325 00	327 30	330 00	332 30	335 00	337 30
11	340 00	342 30	345 00	347 30	350 00	352 30
12	355 00	357 30	0 00	2 30	5 00	7 30
13	10 00	12 30	15 00	17 30	20 00	22 30
14	25 00	27 30	30 00	32 30	35 00	37 30
15	40 00	42 30	45 00	47 30	50 00	52 30
16	55 00	57 30	60 00	62 30	65 00	67 30
17	70 00	72 30	75 00	77 30	80 00	82 30
18	85 00	87 30	90 00	92 30	95 00	97 30
19	100 00	102 30	105 00	107 30	110 00	112 30
20	115 00	117 30	120 00	122 30	125 00	127 30
21	130 00	132 30	135 00	137 30	140 00	142 30
22	145 00	147 30	150 00	152 30	155 00	157 30
23	160 00	162 30	165 00	167 30	170 00	172 30

(e) Minutes and Seconds of GMT

m s	° ′	m s	° ′	m s	° ′	m s	° ′	m s	° ′	m s	° ′
00 00	0 00	01 37	0 25	03 17	0 50	04 57	1 15	06 37	1 40	08 17	2 05
01	0 01	41	0 26	21	0 51	05 01	1 16	41	1 41	21	2 06
05	0 02	45	0 27	25	0 52	05	1 17	45	1 42	25	2 07
09	0 03	49	0 28	29	0 53	09	1 18	49	1 43	29	2 08
13	0 04	53	0 29	33	0 54	13	1 19	53	1 44	33	2 09
17	0 05	01 57	0 30	37	0 55	17	1 20	06 57	1 45	37	2 10
21	0 06	02 01	0 31	41	0 56	21	1 21	07 01	1 46	41	2 11
25	0 07	05	0 32	45	0 57	25	1 22	05	1 47	45	2 12
29	0 08	09	0 33	49	0 58	29	1 23	09	1 48	49	2 13
33	0 09	13	0 34	53	0 59	33	1 24	13	1 49	53	2 14
37	0 10	17	0 35	03 57	1 00	37	1 25	17	1 50	08 57	2 15
41	0 11	21	0 36	04 01	1 01	41	1 26	21	1 51	09 01	2 16
45	0 12	25	0 37	05	1 02	45	1 27	25	1 52	05	2 17
49	0 13	29	0 38	09	1 03	49	1 28	29	1 53	09	2 18
53	0 14	33	0 39	13	1 04	53	1 29	33	1 54	13	2 19
00 57	0 15	37	0 40	17	1 05	05 57	1 30	37	1 55	17	2 20
01 01	0 16	41	0 41	21	1 06	06 01	1 31	41	1 56	21	2 21
05	0 17	45	0 42	25	1 07	05	1 32	45	1 57	25	2 22
09	0 18	49	0 43	29	1 08	09	1 33	49	1 58	29	2 23
13	0 19	53	0 44	33	1 09	13	1 34	53	1 59	33	2 24
17	0 20	02 57	0 45	37	1 10	17	1 35	07 57	2 00	37	2 25
21	0 21	03 01	0 46	41	1 11	21	1 36	08 01	2 01	41	2 26
25	0 22	05	0 47	45	1 12	25	1 37	05	2 02	45	2 27
29	0 23	09	0 48	49	1 13	29	1 38	09	2 03	49	2 28
33	0 24	13	0 49	53	1 14	33	1 39	13	2 04	53	2 29
37	0 25	17	0 50	04 57	1 15	37	1 40	17	2 05	09 57	2 30
01 41		03 21		05 01		06 41		08 21		10 00	

EXPLANATION

These data make possible the determination of the GHA and declination of the Sun for any time during the years 1965-2000. Table 3a gives E(5 + Equation of Time) and declination of the Sun for the argument "Orbit Time" O.T., the latter formed by applying the h correction from Table 3b to the nearest integral hour of GMT. In leap years the upper value of the h correction is to be used for January and February, and the lower h value for the rest of the year. Thus, O.T.'s corresponding to GMT's of 1631 February 29 and 0529 March 1, 1968, are 0400 February 29 and 1600 March 1, respectively.

Corrections to E and declination for O.T. are determined by entering Table 3c with differences between consecutive values of E and declination as horizontal argument, and the vertical column with number of hours of O.T. as vertical argument.

The GHA is obtained by adding to the corrected E the value of the diurnal arc obtained from Tables 3d and 3e. The latter two tables must be entered with argument GMT.

EXAMPLE - October 28, 1978, GMT=$15^h 30^m 01^s$

O.T.=GMT(nearest integral hour)+Corr.(Table 3b)

O.T.=Oct. $28^d 16^h + 01^h$ = Oct. $28^d 17^h$

Table 3a, Oct. 28^d O.T.	$9^\circ 02'(+01')$	S $12^\circ 55'$ (+20')
Table 3c, 17^h O.T.	+01'	+14'
E,Dec., Oct. $28^d 17^h$	$9^\circ 03'$	S $13^\circ 09'$
Table 3d, $15^h 30^m$ GMT	$47^\circ 30'$	
Table 3e, $0^m 01^s$ GMT	00'	
Sum, GHA, Sun	$56^\circ 33'$	
Sum, Dec. Sun		S $13^\circ 09'$

Table 4. Extracts from sight reduction tables for air navigation

N. Lat. {LHA greater than 180°....... Zn=Z; LHA less than 180°.......... Zn=360−Z}

S. Lat. {LHA greater than 180°....... Zn=180−Z; LHA less than 180°.......... Zn=180+Z}

DECLINATION (0°-14°) CONTRARY NAME TO LATITUDE — LAT 32°

4°			5°			6°			7°			8°			9°			10°			11°			12°			13°			14°			
Hc	d	Z	Hc	d	Z	Hc	d	Z	Hc	d	Z	Hc	d	Z	Hc	d	Z	Hc	d	Z	Hc	d	Z	Hc	d	Z	Hc	d	Z	Hc	d	Z	LHA
° ′	′	°	° ′	′	°	° ′	′	°	° ′	′	°	° ′	′	°	° ′	′	°	° ′	′	°	° ′	′	°	° ′	′	°	° ′	′	°	° ′	′	°	
15 26	34	105	14 52	34	106	14 18	35	107	13 43	35	108	13 08	35	108	12 33	35	109	11 58	35	110	11 23	36	111	10 47	36	112	10 11	35	112	09 36	36	113	291
16 15	34	106	15 41	35	106	15 06	35	107	14 31	35	108	13 56	35	109	13 21	35	110	12 46	36	111	12 10	36	111	11 34	36	112	10 58	36	113	10 22	36	114	292
17 04	34	106	16 30	35	107	15 55	35	108	15 20	36	109	14 44	35	110	14 09	36	110	13 33	36	111	12 57	36	112	12 21	36	113	11 45	36	114	11 09	37	114	293
17 53	35	107	17 18	35	108	16 43	35	108	16 08	36	109	15 32	36	110	14 56	36	111	14 20	36	112	13 44	36	113	13 08	36	113	12 32	37	114	11 55	37	115	294
18 42	−35	107	18 07	−36	108	17 31	−35	109	16 56	−36	110	16 20	−36	111	15 44	−36	112	15 08	−37	112	14 31	−36	113	13 55	−37	114	13 18	−37	115	12 41	−37	116	295
19 30	35	108	18 55	36	109	18 19	36	110	17 43	36	111	17 07	36	111	16 31	36	112	15 55	37	113	15 18	37	114	14 41	37	115	14 04	37	116	13 27	38	116	296
20 19	36	109	19 43	36	110	19 07	36	110	18 31	36	111	17 55	37	112	17 18	37	113	16 41	37	114	16 04	37	115	15 27	37	115	14 50	38	116	14 12	37	117	297
21 07	36	109	20 31	36	110	19 55	37	111	19 18	36	112	18 42	37	113	18 05	37	114	17 28	38	114	16 50	37	115	16 13	38	116	15 35	37	117	14 58	38	118	298
21 55	36	110	21 19	37	111	20 42	37	112	20 05	36	112	19 29	38	113	18 51	37	114	18 14	38	115	17 36	37	116	16 59	38	117	16 21	38	117	15 43	39	118	299
22 42	−36	111	22 06	−37	111	21 29	−37	112	20 52	−37	113	20 15	−37	114	19 38	−38	115	19 00	−38	116	18 22	−38	116	17 44	−38	117	17 06	−39	118	16 27	−38	119	300
23 30	37	111	22 53	37	112	22 16	37	113	21 39	37	114	21 02	38	115	20 24	38	115	19 46	38	116	19 08	39	117	18 29	38	118	17 51	39	119	17 12	39	120	301
24 17	37	112	23 40	37	113	23 03	37	114	22 26	38	114	21 48	38	115	21 10	39	116	20 31	38	117	19 53	39	118	19 14	39	119	18 35	39	119	17 56	40	120	302
25 04	37	113	24 27	37	113	23 50	38	114	23 12	38	115	22 34	39	116	21 55	38	117	21 17	39	118	20 38	39	118	19 59	40	119	19 19	39	120	18 40	40	121	303
25 51	37	113	25 14	38	114	24 36	38	115	23 58	39	116	23 19	39	117	22 40	38	117	22 02	40	118	21 22	39	119	20 43	40	120	20 03	40	121	19 23	40	122	304
26 38	−38	114	26 00	−38	115	25 22	−39	116	24 43	−38	117	24 05	−40	117	23 25	−39	118	22 46	−39	119	22 07	−40	120	21 27	−40	121	20 47	−41	121	20 06	−40	122	305
27 24	38	115	26 46	38	116	26 08	39	116	25 29	39	117	24 50	40	118	24 10	39	119	23 31	40	120	22 51	41	121	22 10	40	121	21 30	41	122	20 49	40	123	306
28 11	39	115	27 32	39	116	26 53	39	117	26 14	40	118	25 34	39	119	24 55	40	120	24 15	41	120	23 34	40	121	22 54	41	122	22 13	41	123	21 32	41	124	307
28 56	39	116	28 17	39	117	27 38	39	118	26 59	40	119	26 19	40	120	25 39	41	120	24 58	40	121	24 18	41	122	23 37	41	123	22 56	42	124	22 14	41	124	308
29 42	39	117	29 03	40	118	28 23	40	119	27 43	40	119	27 03	41	120	26 22	40	121	25 42	41	122	25 01	42	123	24 19	41	124	23 38	42	124	22 56	42	125	309
30 27	−39	118	29 48	−40	118	29 08	−41	119	28 27	−40	120	27 47	−41	121	27 06	−41	122	26 25	−42	123	25 43	−41	123	25 02	−42	124	24 20	−43	125	23 37	−42	126	310

DECLINATION (0°-14°) CONTRARY NAME TO LATITUDE — LAT 33°

4°			5°			6°			7°			8°			9°			10°			11°			12°			13°			14°			
Hc	d	Z	Hc	d	Z	Hc	d	Z	Hc	d	Z	Hc	d	Z	Hc	d	Z	Hc	d	Z	Hc	d	Z	Hc	d	Z	Hc	d	Z	Hc	d	Z	LHA
° ′	′	°	° ′	′	°	° ′	′	°	° ′	′	°	° ′	′	°	° ′	′	°	° ′	′	°	° ′	′	°	° ′	′	°	° ′	′	°	° ′	′	°	
15 11	35	105	14 36	36	106	14 00	35	107	13 25	36	108	12 49	36	109	12 13	36	109	11 37	36	110	11 01	36	111	10 25	37	112	09 48	36	113	09 12	37	113	291
15 59	35	106	15 24	36	107	14 48	35	108	14 13	36	108	13 37	36	109	13 01	37	110	12 24	36	111	11 48	37	112	11 11	36	112	10 35	37	113	09 58	37	114	292
16 48	36	106	16 12	36	107	15 36	36	108	15 00	36	109	14 24	36	110	13 48	37	111	13 11	36	111	12 35	37	112	11 58	37	113	11 21	37	114	10 44	37	115	293
17 36	36	107	17 00	36	108	16 24	36	109	15 48	37	110	15 11	36	110	14 35	37	111	13 58	37	112	13 21	37	113	12 44	37	114	12 07	37	114	11 30	38	115	294
18 24	−36	108	17 48	−36	109	17 12	−37	109	16 35	−37	110	15 58	−36	111	15 22	−37	112	14 45	−38	113	14 07	−37	114	13 30	−37	114	12 53	−38	115	12 15	−38	116	295
19 12	37	108	18 35	36	109	17 59	37	110	17 22	37	111	16 45	37	112	16 08	37	113	15 31	38	113	14 53	37	114	14 16	38	115	13 38	30	116	13 00	38	117	296
19 59	36	109	19 23	37	110	18 46	37	111	18 09	37	112	17 32	37	112	16 55	38	113	16 17	38	114	15 39	38	115	15 01	38	116	14 23	38	116	13 45	38	117	297
20 47	37	110	20 10	37	110	19 33	37	111	18 56	38	112	18 18	37	113	17 41	38	114	17 03	38	115	16 25	38	115	15 47	39	116	15 08	38	117	14 30	39	118	298
21 34	37	110	20 57	37	111	20 20	38	112	19 42	37	113	19 05	38	114	18 27	38	114	17 49	39	115	17 10	38	116	16 32	39	117	15 53	39	118	15 14	39	118	299
22 21	−37	111	21 44	−38	112	21 06	−37	113	20 29	−38	113	19 51	−39	114	19 12	−38	115	18 34	−39	116	17 55	−39	117	17 16	−39	118	16 37	−39	118	15 58	−39	119	300
23 08	37	112	22 31	38	112	21 53	38	113	21 15	39	114	20 36	38	115	19 58	39	116	19 19	39	117	18 40	39	117	18 01	39	118	17 22	40	119	16 42	40	120	301
23 55	38	112	23 17	38	113	22 39	38	114	22 01	39	115	21 22	39	116	20 43	39	116	20 04	39	117	19 25	40	118	18 45	40	119	18 05	39	120	17 26	41	120	302
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25 28	39	114	24 49	39	115	24 10	39	115	23 31	39	116	22 52	39	117	22 13	40	118	21 33	40	119	20 53	40	119	20 13	41	120	19 32	40	121	18 52	41	122	304
26 13	−38	114	25 35	−39	115	24 56	−40	116	24 16	−39	117	23 37	−40	118	22 57	−40	119	22 17	−40	119	21 37	−41	120	20 56	−41	121	20 15	−41	122	19 34	−41	123	305
26 59	39	115	26 20	39	116	25 41	40	117	25 01	40	118	24 21	40	118	23 41	40	119	23 01	41	120	22 20	41	121	21 39	41	122	20 58	41	122	20 17	42	123	306
27 45	40	116	27 05	39	117	26 26	40	118	25 46	41	118	25 05	40	119	24 25	41	120	23 44	41	121	23 03	41	122	22 22	42	122	21 40	41	123	20 59	42	124	307
28 30	40	117	27 50	40	117	27 10	40	118	26 30	41	119	25 49	41	120	25 08	41	121	24 27	41	122	23 46	42	122	23 04	42	123	22 22	42	124	21 40	42	125	308
29 15	40	117	28 35	41	118	27 54	40	119	27 14	41	120	26 33	42	121	25 51	41	122	25 10	42	122	24 28	42	123	23 46	42	124	23 04	43	125	22 21	42	125	309
29 59	−40	118	29 19	−41	119	28 38	−41	120	27 57	−41	121	27 16	−42	121	26 34	−42	122	25 52	−42	123	25 10	−42	124	24 28	−43	125	23 45	−43	125	23 02	−43	126	310

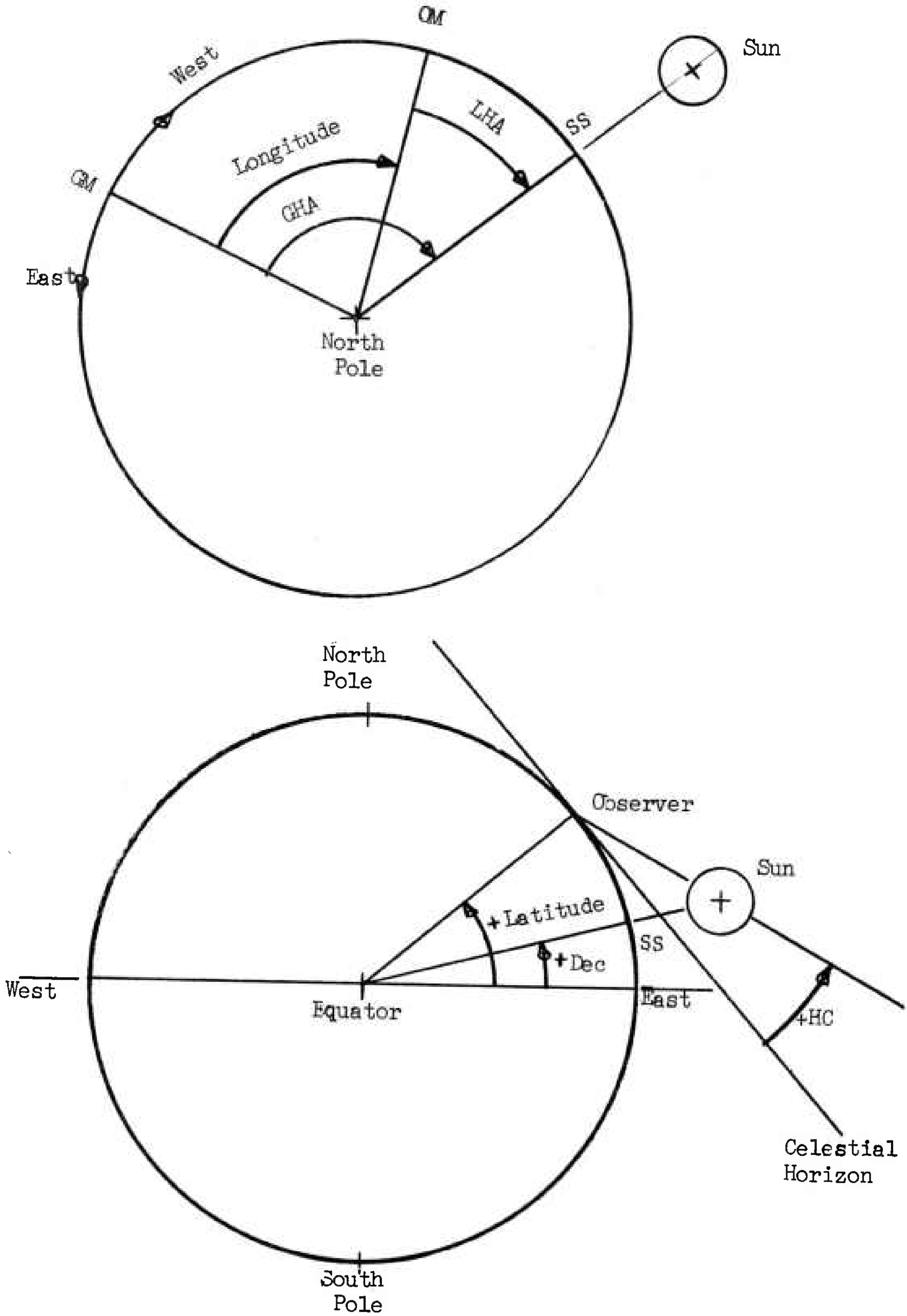

Figure 1. Celestial angle relations.

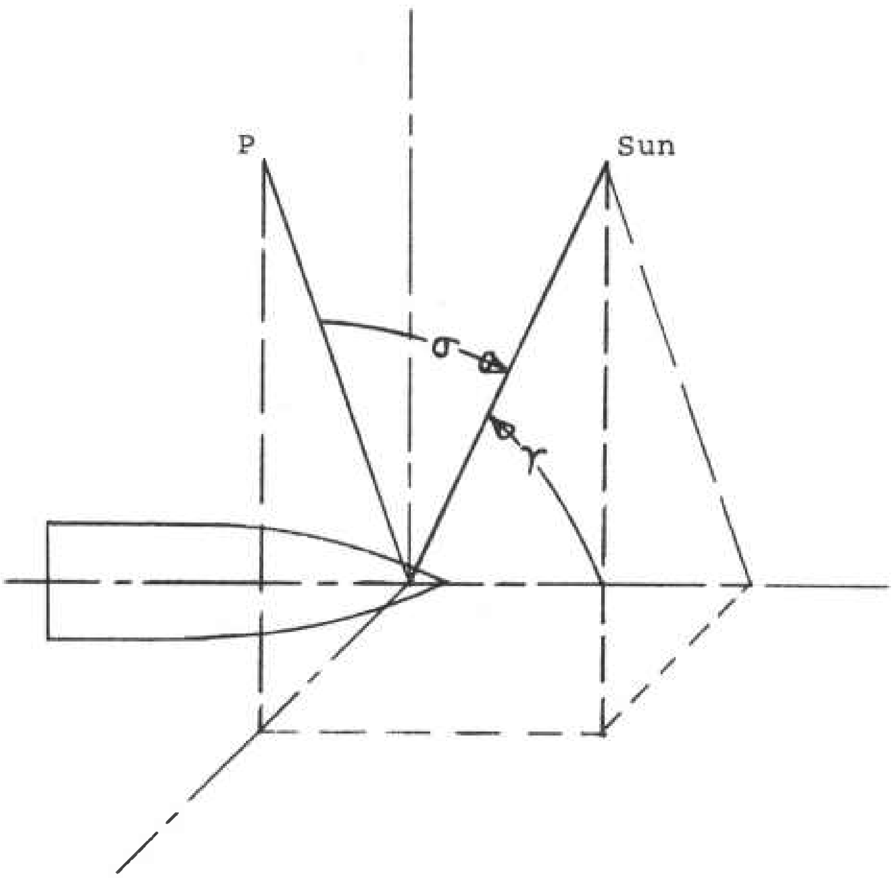

Figure 2. Definition of gamma and sigma.

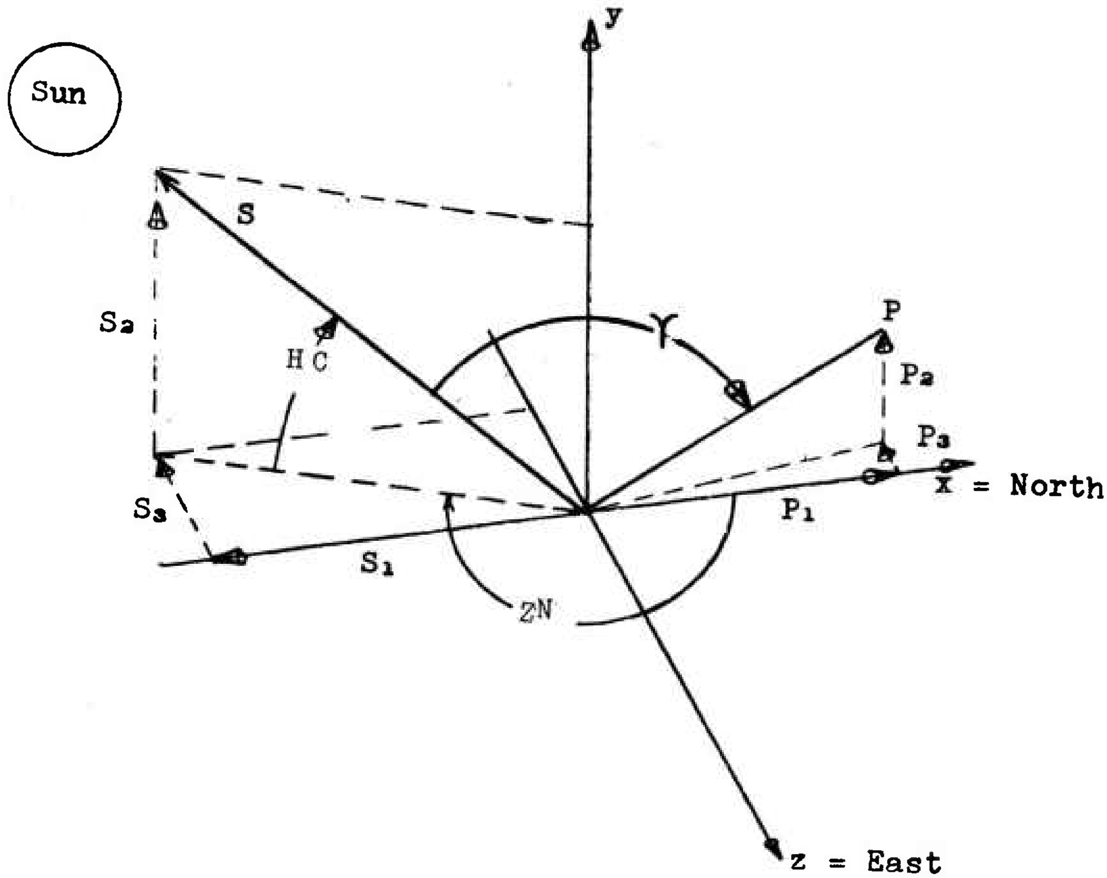

Figure 3. Sun-to-projectile angle resolution and sun s elevation and azimuth.

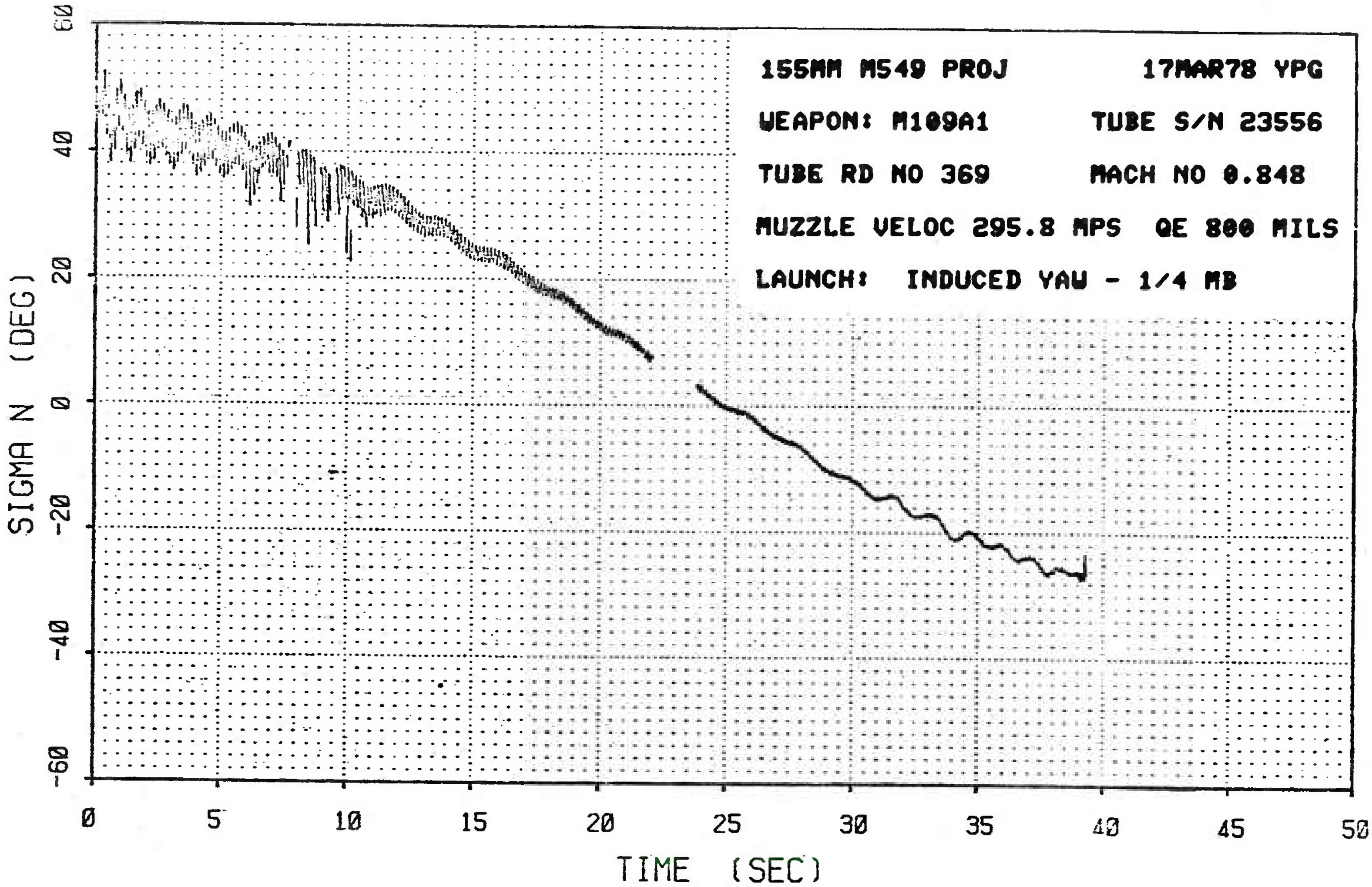

Figure 4. Actual sigma N vs time of a 155 mm M549 projectile.

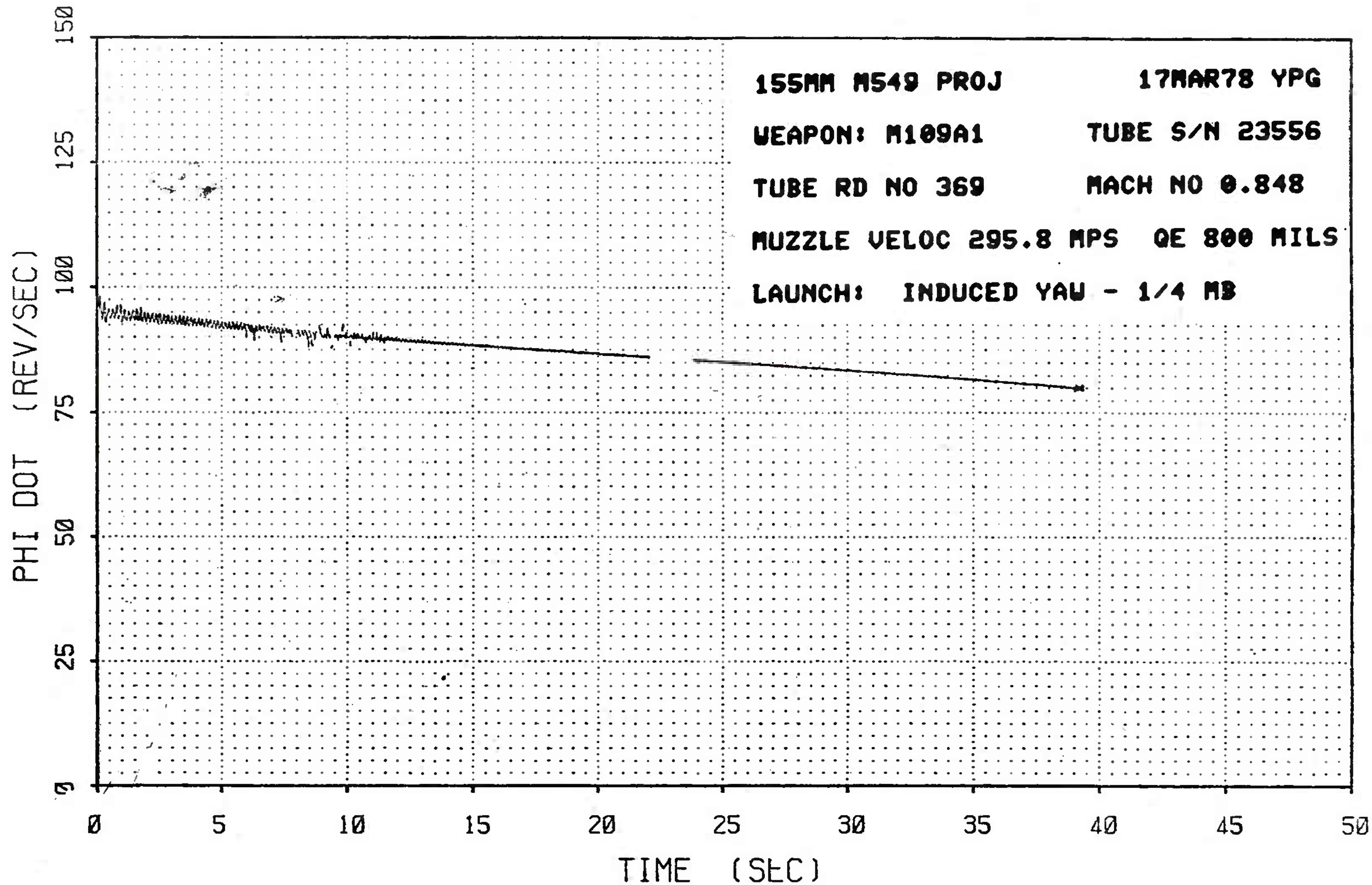

Figure 5. Actual phi dot vs time of a 155 mm M549 projectile.

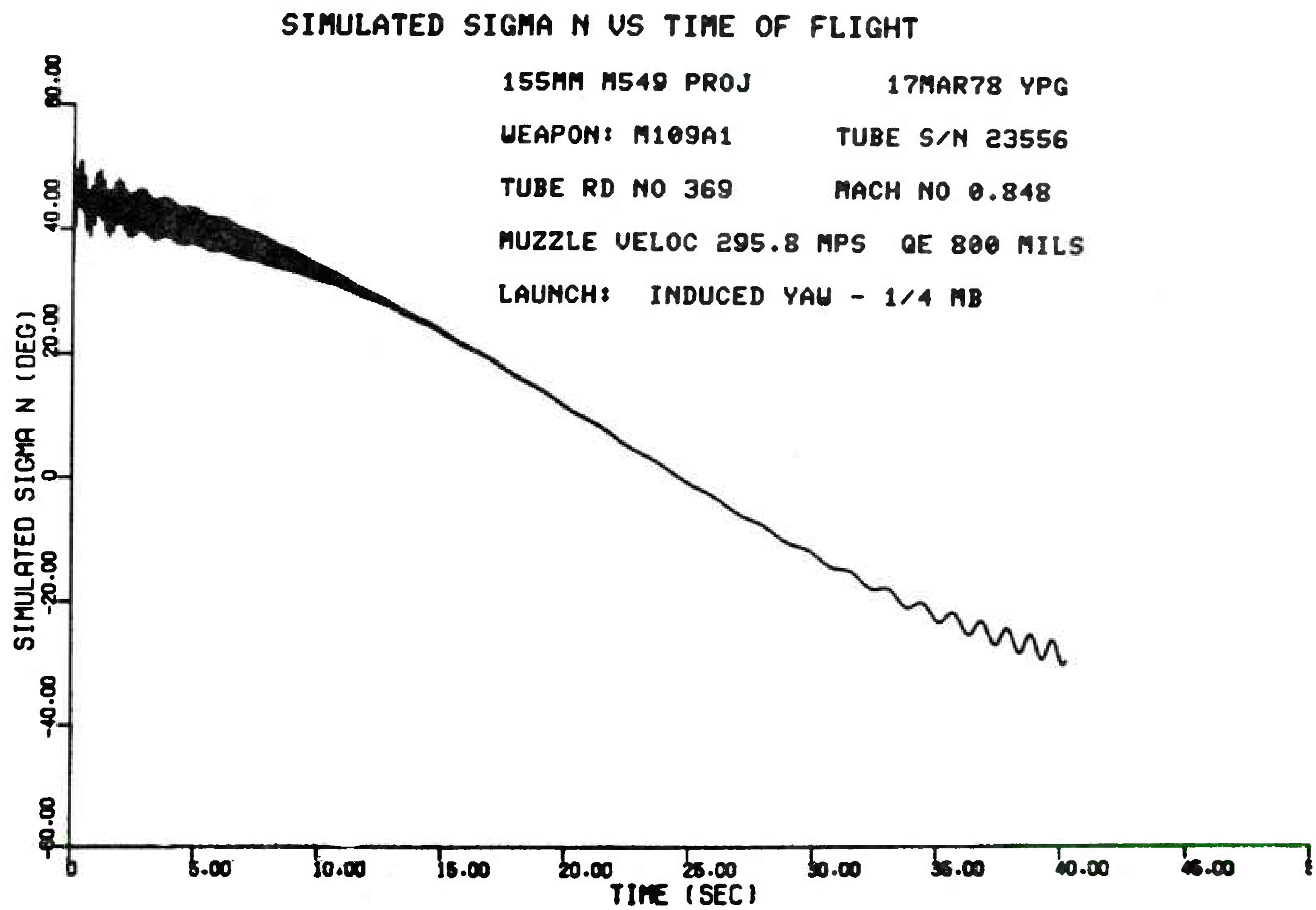

Figure 6. Simulated sigma N vs time of a 155 mm M549 projectile.

APPENDIX A

INPUT AND OUTPUT FOR COMPUTER PROGRAM "SAZEL"

Description of Input and Output of SAZEL

To find the azimuth and elevation of the sun using the computer program, SAZEL, as listed in Appendix B, data are input on one computer card as follows:

INPUT

Column No.	Item	Format
1-2	NDAY, numerical day of month	I2
10-11	NMONTH, numerical month of year	I2
20-23	NYEAR, numerical year A.D. (1978-2000 only)	I4
30-31	NHOUR, GMT hours	I2
32-33	NMIN, minutes	I2
50-59	WLONG, longitude, degrees	F9.4
60-69	WLAT, latitude, degrees	F9.4

EXAMPLE

The example used in table 3 and 4 is chosen for comparative purposes.

October 28, 1978; GMT= 1530
Yuma Proving Ground; Longitude=114.3028 deg, Latitude=32.8811 deg

Column No.	Card Item
1-2	28
10-11	10
20-23	1978
30-31	15
32-33	30
50-59	114.3028
60-69	32.8811

OUTPUT

ODAY	OTIME (Z)	GHA	AZIMUTH	DECLINATION	ELEVATION
302	1600	56.5333	119.8569	-13.1392	18.2251

APPENDIX B

LISTING OF COMPUTER PROGRAM "SAZEL"

```
      PROGRAM SAZEL (INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
C
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C     CALCULATES THE SUN POSITION (AZIMUTH ANO ELEVATION) WITH RESPECT
C     TO OBSERVER POSITION (LATITIUOE,LONGITUOE, ANO GREENWICH TIME)
C
C
C     WRITTEN BY E. F. BROWN, 1 AUG 78, WITH REFERENCES TO AIR FORCE
C     MANUAL 51-40 VOLUME 1, AIR NAUTICAL ALMANAC, CELESTIAL HO 249,
C     VOLUMES, PERSONAL NOTES FROM UNDERGRADUATE NAVIGATION TRAINING,
C     AIR TRAINING COMMANO, US AIR FORCE, MATHER AFB,1971
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C
C     NOAY=NUMERICAL OAY OF MONTH
C     NMONTH=NUMERICAL MONTH OF YEAR
C     NYEAR=NUMERICAL YEAR AO
C     NHOUR=NUMERICAL GREENWICH HOUR (ZULU)
C     MIN=NUMERICAL MINUTES (TIME)
C     WLONG=OBSERVER LONGITUOE,OEGREES
C           + WEST
C           - EAST
C     WLAT=OBSERVER LATITUOE,OEGREES
C           + NORTH
C           - SOUTH
C     DATEN=JULIAN DATE TO COMPUTE SUN COOROINATES, MAY DIFFER
C            FROM INPUT OATE
C     GHAS=GREENWICH HOUR ANGLE, ALWAYS MEASURED WEST FROM 0 DEGREE
C           LONGITUOE, OEGREES
C     OECS=SUN OECLINATION MEASUREO FROM 0 DEGREE LATITUOE, OEGREES
C           + NORTH
C           - SOUTH
C     TIME=JULIAN SUN TIME TO COMPUTE SUN COORDINATES, MAY
C           OIFFER FROM INPUT DATE
C     AZHBO=AZIMUTH OF SUN FROM TRUE NORTH MEASURED CLOCKWISE
C            FROM OBSERVERS POSITION, DEGREES
C     HB=ELEVATION OF SUN MEASURED FROM OBSERVERS GROUND
C        LEVEL HORIZON, DEGREES
C           + ABOVE HORIZON
C           - BELOW HORIZON
C
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
      DIMENSION MONTH (12,2),CORR(45)
      OIMENSION OEC1(186),EPIC1(176),OECA1(176)
      OIMENSION DEC2(180),EPIC2(190),DECA2(190)
      INTEGER OATEJ,OATEN,TIME
C
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C
```

```
C       EPIC1 AND EPIC2 CONTAINS THE ECLIPTIC ANGULAR POSITION
C       OF THE 5UN AS A FUNCTION OF JULIAN DATE
C
C
C       DECI AND DEC2 CONTAIN THE 5INUS0IDAL PATH OF THE 5UN
C       AS A FUNCTION OF JULIAN OATE
C
C
C       OECA1 AND OECA2 CONTAIN THE OECLINATION INCREMENT FROM
C       DAY TO DAY AS A FUNCTION OF JULIAN OATE
C
C
        OATA EPIC1/4.1833,4.0667,3.95,3.8333,3.7167,3.6,3.5,3.3833,
       $3.2833,3.1833,3.0833,2.9833,2.8833,2.7833,2.7,2.6167,
       $2.5167,2.4333,2.3667,2.2833,2.2167,2.1333,2.0667,2.0,
       $1.95,1.8833,1.8333,1.7833,1.7333,1.6833,1.65,
       $1.6167,1.5833,1.55,1.5167,1.5,1.4833,1.4667,1.45,1.4333,1.4333,
       $1.4333,1.4333,1.4333,1.4333,1.45,1.45,1.4667,1.4833,1.5,1.5333,
       $1.55,1.5833,1.6167,1.65,1.6833,1.7333,1.7667,1.8167,1.8667,1.8667,
       $1.9167,1.9667,2.0167,2.0667,2.1167,2.1833,2.2333,2.3,2.3667,
       $2.4333,2.5,2.5667,2.6333,2.7,2.7667,2.8333,2.9167,2.9833,3.0667,
       $3.1333,3.2,3.2833,3.3667,3.4333,3.5167,3.5833,3.6667,3.7333,
       $3.8167,3.8833,3.9667,4.0333,4.1167,4.1833,4.2667,4.3333,4.4,
       $4.4667,4.55,4.6167,4.6833,4.75,4.8167,4.8833,4.9333,5.0,5.0667,
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       $5.7333,5.7,5.6667,5.6333,5.6,5.55,5.5167,5.4667,5.4333,
       $5.3833,5.35,5.3,5.25,5.2,5.15,5.1,5.05,5.0,4.95,4.9,4.8333,4.7833,
       $4.7333,4.6833,4.6167,4.5667,4.5167,4.4667/
C
C
        DATA EPIC2/4.4,4.35,4.3,4.25,4.2,
       $4.15,4.1,4.05,4.0,3.95,3.9167,3.8667,3.8167,3.7833,3.75,3.7,
       $3.6667,3.6333,3.6,3.5833,3.55,3.5167,3.5,3.4833,3.4667,3.45,
       $3.4333,3.4167,3.4,3.4,3.4,3.3833,3.3833,3.3833,3.4,3.4,3.4167,
       $3.4167,3.4333,3.45,3.4667,3.5,3.5167,3.55,3.5833,3.6167,3.65,
       $3.6833,3.7167,3.7667,3.8,3.85,3.9,3.95,4.0,4.0667,4.1167,4.1833,
       $4.2333,4.3,4.3667,4.4333,4.5,4.5667,4.6333,4.7167,4.7833,4.8667,
       $4.95,5.0167,5.1,5.1833,5.2667,5.35,5.4333,5.5167,5.6,5.6833,
       $5.7833,5.8667,5.95,6.0333,6.1333,6.2167,6.3,6.4,6.4833,6.5667,
       $6.6667,6.75,6.8333,6.9333,7.0167,7.1,7.1833,7.2667,7.35,7.4333,
       $7.5167,7.6,7.6833,7.75,7.8333,7.9167,7.9833,8.05,8.1167,8.2,
       $8.2667,8.3167,8.3833,8.45,8.5,8.5667,8.6167,8.6667,8.7167,8.7667,
       $8.8,8.85,8.8833,8.9167,8.95,8.9833,9.0,9.0333,9.05,9.0667,9.0833,
       $9.0833,9.1,9.1,9.1,9.1,9.0833,9.0833,9.0667,9.05,9.0333,9.0,
       $8.9833,8.95,8.9167,8.8667,8.8333,8.7833,8.7333,8.6833,8.6333,
       $8.5667,8.5,8.4333,8.3667,8.3,8.2333,8.15,8.0667,7.9833,7.9,7.8,
       $7.7167,7.6167,7.5167,7.4167,7.3167,7.2,7.1,7.0,6.8833,6.7667,
       $6.65,6.5333,6.4167,6.3,6.1833,6.05,5.9333,5.8167,5.6833,5.5667,
       $5.4333,5.3167,5.1833,5.0667,4.95,4.8167,4.7,4.5667,4.45,4.3333/
C
```

```
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     $5,-20.8667,-20.667,-20.467,-20.25,-20.033,-19.817,-19.583,-19.35,-
     $19.117,-18.867,-18.617,-18.35,-18.083,-17.817,-17.55,-17.267,-16.9
     $83,-16.7,-16.4,-16.1,-15.8,-15.5,-15.183,-14.867,-14.55,-14.217,-1
     $3.883,-13.55,-13.217,-12.883,-12.533,-12.2,-11.85,-11.483,-11.133,
     $-10.767,-10.417,-10.05,-9.683,-9.317,-8.933,-8.567,-8.183,-7.817,-
     $7.817,-7.433,-7.05,-6.667,-6.283,-5.9,-5.517,-5.117,-4.733,-4.333,
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     $,9.9,10.267,10.617,10.967,11.317,11.65,12.,12.333,12.667,13.,13.31
     $7,13.633,13.967,14.283,14.583,14.9,15.2,15.5,15.783,16.083,16.367,
     $16.65,16.917,17.2,17.467,17.717,17.983,18.233,18.483,18.717,18.967
     $,19.183,19.417,19.633,19.85,20.067,20.267,20.467,20.65,20.833,21.0
     $17,21.2,21.367,21.517,21.683,21.833,21.967,22.1,22.233,22.367,22.4
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     $283,23.333,23.367,23.4,23.417,23.433,23.433,23.45,23.433,23.417,23
     $.4,23.383,23.35,23.317,23.267,23.217,23.15,23.083,23.017,22.933/
C
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     $67,17.4,17.133,16.867,16.6,16.317,16.033,15.75,15.45,15.15,14.85,1
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     $23.4,-23.417,-23.433,-23.45,-23.433,-23.433,-23.417,-23.383,-23.35
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C
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C
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C     CORR CONTAINS THE HOURLY CORRECTION FOR EACH YEAR TO CORRECT
C     THE MOTION OF THE SUN FOR GREENWICH HOUR ANGLE AND DECLINATION
C
      DATA CORR/4.,-1.,-7.,-13.,5.,-1.,-7.,-12.,6.,0.,-6.,-12.,7.,1.,
     $-5.,-11.,7.,1.,-4.,-10.,8.,2.,-4.,-9.,9.,3.,-3.,-9.,10.,4.,
     $-2.,-8.,10.,4.,-1.,-7.,11.,12.,12.,13.,14.,15.,15.,16.,17./
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
      OATA MONTH /0,31,59,90,120,151,181,212,243,273,304,334,
     $            0,31,60,91,121,152,182,213,244,274,305,335/
      OATA P1,P12/3.141592654,6.283185307/
      READ(5,1) NDAY,NMONTH,NYEAR,NHOUR,MIN,WLONG,WLAT
    1 FORMAT (I2,7X,I2,7X,I4,5X,2I2,5X,2F9.4)
      IF (NYEAR.LT.1965.OR.NYEAR.GT.2000) WRITE (6,101)
  101 FORMAT (1H1,*PROGRAM VALIO INCLUSIVE FROM YEARS 1965 THRU 2000*)
      MYEAR=NYEAR-1900
      HC=0.0
      IF (MIN.GT.30) HC=100.
```

```
      HO=FLOAT(NHOUR*100)
C
C     COMPUTES IF NYEAR IS A LEAP YEAR
      GO TO (100,110,110,110),MOD(NYEAR-1904,4)+1
C
  100 IYEAR=2
      N=MYEAR-64
      GO TO 120
  110 CONTINUE
      IYEAR=1
      N=MYEAR-64
  120 CONTINUE
      DATEJ=MONTH(NMONTH,IYEAR)+NDAY
      IF (IYEAR.EQ.2.AND.DATEJ.GT.60) N=((MYEAR+12)/4)+17
      ADD=CORR(N)*100.
      CH=HO+HC+ADD
      DATEN=DATEJ
      IF (CH.LT.0.0) DATEN=DATEN-1
      IF (CH.GT.2400.) DATEN=DATEN+1
      IF (CH.GT.HO.AND.CH.EQ.2400.) DATEN=DATEN+1
      IF (IYEAR.EQ.1.AND.DATEJ.GT.59) DATEN=DATEJ+1
      IF (DATEN.EQ.367) DATEN=1
      IF (DATEN.EQ.0) DATEN=366
      TI=CH
      IF (CH.GT.2400.) TI=CH-2400.
      IF (CH.LT.0.0) TI=CH+2400.
      TIME=IFIX(TI)
      IF (DATEN.LE.186) TILT=DEC1(DATEN)
      IF (DATEN.GT.186) TILT=DEC2(DATEN-186)
      IF (DATEN.LE.176) CTILT=(TI/2400.)*DECA1(DATEN)
      IF (DATEN.GT.176) CTILT=(TI/2400.)*DECA2(DATEN-176)
      IF (DATEN.LE.176) ZEN=EPIC1(DATEN)
      IF (DATEN.GT.176) ZEN=EPIC2(DATEN-176)
      ZENS=FLOAT(NHOUR)*15.+FLOAT(MIN)*(15./60.)+175.
      ZHOR=ZENS
      IF (ZENS.GT.360.) ZHOR=ZENS-360.
      GHAS=ZEN+ZHOR
      DECS=TILT+CTILT
      RAD=.0174533
      WLATR=WLAT*RAD
      WLONGR=WLONG*RAD
      DECL=DECS*RAD
      SINPHI=SIN(WLATR)
      COSPHI=COS(WLATR)
      SINDEC=SIN(DECL)
      COSDEC=COS(DECL)
      GHA=GHAS*RAD
      IF (GHA.LT.0) GHA=PI2+GHA
      TLHA=GHA-WLONGR + PI2
      IF (TLHA.LT.PI) T=TLHA
      IF (TLHA.GE.PI) T=PI2-TLHA
      IF (TLHA.GE.PI2) T=TLHA-PI2
      COST=COS(T)
```

```
      ARG1=SINPHI*SINDEC+COSPHI*COSDEC*COST
      H=ASIN(ARG1)
      COHS=COS(H)
      SIHN=SIN(H)
      ARG2=(SINDEC-SINPHI*SIHN)/(COSPHI*COHS)
      Z=ACOS(ARG2)
      IF (TLHA.LT.PI) AZHB=PI2-Z
      IF (TLHA.GE.PI) AZHB=Z
      IF (TLHA.GE.PI2) AZHB=PI2-Z
      AZHBD=AZHB/RAD
      HB=H/RAD
      WRITE(6,705)
  705 FORMAT(1H1,5X,*INPUT*,//)
      WRITE(6,703)
  703 FORMAT(5X,*DAY*,2X,*MONTH*,2X,*YEAR*,2X,*TIME  (Z)*,2X,*LONGITUDE*,
     $2X,*LATITUDE*)
      WRITE(6,704) NDAY,NMONTH,NYEAR,NHOUR,MIN,WLONG,WLAT
  704 FORMAT (5X,I3,4X,I2,3X,I4,4X,2I2,4X,F9.4,2X,F8.4,//)
      WRITE(6,702)
  702 FORMAT(5X,*OUTPUT*,//)
      WRITE(6,706)
  706 FORMAT (6X,*ODAY*,2X,*OTIME  (Z)*,3X,*GHA*,5X,*AZIMUTH*,2X,*DECLINA
     $TION*,2X,*ELEVATION*)
      WRITE (6,707) DATEN,TIME,GHAS,AZHBD,DECS,HB
  707 FORMAT (7X,I3,4X,I4,4X,F8.4,1X,F8.4,3X,F8.4,4X,F8.4)
      STOP
      END
```

GLOSSARY

Azimuth	The angle measured clockwise from true north to a line passing through the observer and subpoint of the sun
Celestial horizon	The tangent plane to the earth passing through the observer's position
Declination	The angular distance to the sun measured north or south through 90° from the equator to the subpoint of the sun
Elevation	The angular distance of the sun above the celestial horizon
Greenwich Hour Angle	The angular distance measured from the Greenwich meridian westward through 360° to the meridian passing through the subpoint of the sun
Greenwich Meridian	The prime meridian which passes through Greenwich, England, from which longitude is measured east or west
Greenwich Mean Time	Local time at the Greenwich meridian measured by reference to the mean sun. It is the angle measured along the equator (and converted to time) from the Greenwich meridian westward through 360° to the meridian passing through the subpoint of the mean sun
IZREF	A time conversion to express local mean time as Greenwich mean time
Latitude	Angular distance measured north or south of the equator along a meridian, 0° through 90°
Longitude	The angular distance east or west of the Greenwich meridian, measured along a line of parallel from 0° to 180°
Local Hour Angle	The angular distance measured from the observer's meridian westward through the subpoint of the sun

Local Mean Time	Local time at the observer's meridian measured by reference to the mean sun. It is the angle measured along the equator (and converted to time) from the observer's meridian westward through 360° to the meridan passing through the subpoint of the mean sun
Meridian	Imaginary line on the earth connecting points of equal longitude
Parallel	Imaginary line on the earth connecting points of equal latitude
Subpoint	That point on the earth's surface directly beneath a celestial body
Time	Usually expressed in four numerals (0001 thru 2400) where there are 24 hours in a day and 60 minutes to one hour. 6:29 PM would be expressed as 1829
Z or Zulu time	An expression indicating Greenwich mean time

LIST OF SYMBOLS

Dec	Declination of the sun, deg
DOF	Degrees-of-freedom
GHA	Greenwich Hour Angle of the sun, deg
GM	Greenwich Meridian, 0° longitude
GMT	Greenwich Mean Time, hours
HC	Elevation of the sun, deg
IZREF	Time conversion, hours
LHA	Local Hour Angle of the sun, deg
LMT	Local Mean Time, hours
OM	Observer's meridian, deg of longitude
P_1, P_2, P_3	Directional cosines of missile position, P, as used in 6-DOF trajectory program (earth frame)
S_1, S_2, S_3	Directional cosines of sun position, S, (earth frame)
SS	Sun's subpoint meridian, deg
ZN	True azimuth of the sun, deg
γ	Yaw sonde acquisition angle between the sun and projectile axis, deg
σ	Angle between the sun and transverse plane perpendicular to projectile longitudinal axis, deg

SIGN CONVENTION

Dec	North + South -
HC	Above celestial horizon + Below celestial horizon -
UZREF	East longitude position - West longitude position +
Latitude	North + South -
Longitude	East + West -
Sun	Forward of projectile + Aft of projectile -
ZN	Clockwise +

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